

Quantitating Physical Activity in COPD Using a Triaxial Accelerometer*

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Study objective: To determine the reliability, validity, and stability of a triaxial accelerometer for walking and daily activity measurement in a COPD sample.

Design: Cross-sectional, correlational, descriptive design.

Setting: Outpatient pulmonary rehabilitation program in a university-affiliated Veterans Affairs medical center.

Participants: Forty-seven outpatients (44 men and 3 women) with stable COPD (FEV₁, 37% predicted; SD, 16%) prior to entry into a pulmonary rehabilitation program.

Measurements and results: Test-retest reliability of a triaxial movement sensor (Tritrac R3D Research Ergometer; Professional Products; Madison, WI) was evaluated in 35 of the 47 subjects during three standardized 6-min walks (intraclass correlation coefficient [rICC] 0.84). Pearson correlations evaluated accelerometer concurrent validity as a measure of walking (in vector magnitude units), compared to walking distance in all 47 subjects during three sequential 6-min walks (0.84, 0.85, and 0.95, respectively; $p < 0.001$). The validity of the accelerometer as a measure of daily activity over 3 full days at home was evaluated in all subjects using Pearson correlations with other indicators of functional capacity. The accelerometer correlated with exercise capacity (maximal 6-min walk, $r = 0.74$; $p < 0.001$); level of obstructive disease (FEV₁ percent predicted, $r = 0.62$; $p < 0.001$); dyspnea (Functional Status and Dyspnea Questionnaire, dyspnea over the past 30 days, $r = 0.29$; $p < 0.05$); and activity self-efficacy (Activity Self-Efficacy Questionnaire, $r = 0.43$; $p < 0.01$); but not with self-report of daily activity (Modified Activity Recall Questionnaire, $r = 0.14$; not significant). Stability of the accelerometer to measure 3 full days of activity at home was determined by an rICC of 0.69.

Conclusions: This study provides preliminary data suggesting that a triaxial movement sensor is a reliable, valid, and stable measure of walking and daily physical activity in COPD patients. It has the potential to provide more precise measurement of everyday physical functioning in this population than self-report measures currently in use, and measures an important dimension of functional status not previously well-described.

(CHEST 2000; 117:1359-1367)

Key words: ambulatory monitoring; chronic limitation of activity; COPD; exercise

Abbreviations: ASEQ = Activity Self-Efficacy Questionnaire; FSDQ = Functional Status and Dyspnea Questionnaire; MARQ = Modified Activity Recall Questionnaire; 6MDW = 6-min walk test; MS = multiple sclerosis; NS = not significant; rICC = intraclass correlation coefficient; VMU = vector magnitude units

Physical inactivity is a major risk factor for a multitude of illnesses, and is also a mediator in the familiar dyspnea-inactivity-deconditioning spiral, wherein dyspnea, fatigue, and other symptoms produce functional impairment and disability in pulmonary disease. Precise quantitation of physical activity

is especially important in measuring the outcomes of interventions in frail, sedentary populations, such as COPD and the elderly, because small improvements in physical functioning such as walking and balance

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The research reported here was supported by the Department of Veterans Affairs, Veterans Health Administration, Health Services Research and Development Service (NRI 95-082.1). Dr. Steele is the Respiratory Clinical Nurse Specialist at VA Puget Sound Health Care System, Seattle, WA. Manuscript received June 9, 1999; revision accepted January 27, 2000.

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may translate into significantly improved higher-order function and life quality. Nonetheless, although daily, "free-living" physical activity is of interest to investigators and clinicians alike, methods to precisely quantitate this vital dimension of function have only been recently available.

Methods in current use for measuring daily activity include direct observation, self-report questionnaires and diaries, radioisotope techniques (doubly-labeled water measurement of energy expenditure), and heart rate monitoring, a correlate of physical activity. These methods suffer from several problems. Direct observation is both time-consuming and intrusive, and self-report questionnaires and diaries that rely on memory are imprecise, especially in the elderly, and are time-intensive for subjects. Radioisotope methodology is both costly and technologically complex, and heart rate monitoring is both expensive and imprecise in patients with COPD whose heart rates may vary due to medication use and other causes unrelated to physical activity. In addition, neither radioisotope and heart rate monitoring technologies are capable of providing information on specific patterning of activity. A new generation of inexpensive digital pedometers are now available that measure walking fairly well in active groups, but suffer from the inability to accurately measure body movement during slow walking.¹ Accelerometer movement sensors that use a piezoelectric bender element transducer are a practical alternative to other methods, providing a high degree of precision across a wide range of activity levels at relatively low cost. Single-axis accelerometers, such as the Caltrac (HemoKinetics; Madison, WI), measure movement in one plane and have been widely used to study physical activity and energy consumption in healthy young people and the elderly,²⁻⁴ and in patients with COPD.⁵ In addition to having only one plane of measurement, a major disadvantage of the Caltrac accelerometer is inadequate data storage and retrieval technology, which requires study subjects to read and record output from the device when measurement is carried out over days.

More recently, a new generation of multi-axis accelerometers have been developed that have improved sensitivity and are more suitable for research purposes.^{6,7} These devices have been compared to doubly labeled water to study energy expenditure in normal, active people,⁸ and to study activity in relatively sedentary clinical populations, including nursing home residents,⁹ outpatients with multiple sclerosis (MS),¹⁰ and obese children.^{11,12} Using the Tritrac accelerometer (Tritrac R3D Research Ergometer; Professional Products; Madison, WI), Kochersberger et al⁹ were able to differentiate sed-

entary, moderately active, and active nursing home residents ($p = 0.0001$) and between specific activities of varying intensity ($p = 0.0001$). These investigators also found the device stable over 7 days (intraclass correlation coefficient [rICC] = 0.81), but found that 20% of subjects were not compliant in wearing the devices. Ng and Kent-Braun¹⁰ compared daily activity measured by the same device and by self-report measured by the 7-day Activity Recall Questionnaire⁸ in a group of outpatients with MS, and sedentary and active control subjects. They found that the accelerometer was capable of differentiating daily activity between the three groups ($p < 0.001$), whereas the 7-day Activity Recall Questionnaire was not. They also found that the device could differentiate sedentary from active groups. It is probable that neither of the groups studied by these investigators was more functionally limited than persons with severe COPD; thus, the ability of a triaxial accelerometer to measure activity in such a highly sedentary group remains in question. In a series of studies of Tritrac accelerometer measurement of activity in obese children, Epstein et al¹¹ and Coleman et al,¹² like Ng and Kent-Braun,¹⁰ found the device poorly correlated with self-report of activity. These investigators also found that the two measures of activity did not share the same predictors, suggesting that different activity dimensions were being measured. They were also able to differentiate the relative contributions of the three movement vectors to general activity in this group, but did not make inferences relative to walking specifically.

Accelerometer measurement of walking would assist greatly in clarifying the role of walking behavior as a marker and perhaps determinant of physical functioning in the elderly and persons with chronic illness. Walking is the activity targeted for improvement in most pulmonary rehabilitation programs and other health-maintenance regimens aimed at improving physical functioning, prolonging life, and preventing illness associated with sedentary living.^{13,14} The purpose of this preliminary investigation was to evaluate reliability, validity, and stability of a triaxial accelerometer in the measurement of activity during the 6-min walk test (6MDW), and also during daily activity measurement at home in a sedentary COPD population.

MATERIALS AND METHODS

Two separate measurement conditions were used to estimate validity, reliability, and stability of the accelerometer in a sample of outpatients with stable, moderate to severe COPD. The first examined reliability and validity of the instrument to measure walking behavior during repeated 6MDWs; the second investigated validity of the accelerometer to measure daily activity over

a 3-day period of continuous free-living at home, and stability of the measurement during this period.

Subjects

A convenience sample of 47 outpatients with stable COPD (chronic bronchitis, emphysema, or both) and dyspnea were recruited by the study coordinator from patients referred to an 8-week pulmonary rehabilitation program that included exercise and educational components. Stable COPD was defined as no persistent change in FEV₁ in liters > 10% during the past year. Patients with a COPD exacerbation in the past 2 weeks, or who had severe, unstable cardiovascular disease or a rapidly declining clinical course were excluded. Other exclusion criteria were recent history (6 months) of substance abuse, and neuromuscular or mental problems precluding full participation in the pulmonary rehabilitation program. None of the participants were engaging in > 30 min of exercise for > 3 d/wk prior to program entry. The study was approved by the Human Subjects Committee of the University of Washington, and informed consent was obtained from all study participants. Sample characteristics are included in Table 1.

Measures

Physical Activity-Accelerometer: The Tritrac R3D accelerometer was used in this study to measure physical activity. The accelerometer is worn at the waist, close to the body in a padded pouch; the devices were worn on the side of the nondominant arm to prevent undue contact with the device. The device is about the size of a small cellular phone, and data sampling relies on a 9-V operating battery and a 3-V lithium backup battery, which allows data collection for up to 60 days. The device samples movement at a rate of 10 Hz, and analog-to-digital-converted data is recorded every second and summed to produce 1-min epochs of activity. Movement is measured in three dimensions by three accelerometers oriented at right angles to one another, each having a frequency response of 0.1 to 16 Hz. The frequency response is set to capture the range of human movement, but to filter out rapid vibrations such as those associated with vehicular transportation; having subjects wear the device when in a vehicle further blunts vibratory signals. Accelerometer output (acceleration) is measured in the three dimensions (X [anteroposterior], Y

[vertical], and Z [mediolateral] vectors), and then integrated to represent movement as velocity over time using the square root of the sum of squares of each individual vector. The integrated signal for movement over time is represented by vector magnitude units (VMU).

$$VMU = \sqrt{x^2 + y^2 + z^2}^{15}$$

In addition, activity calories (from movement) and total calories (activity calories plus basal calories) may also be computed by the device using a modification of the Harris-Benedict equation for calculating basal metabolism from preprogrammed subject data, including gender, height, weight, and age. Only movement data (VMU) was used in this analysis.

Data was stored and retrieved using a DOS-compatible software program supplied by the manufacturer. VMU as well as data from X, Y, and Z vectors were individually summed over the duration of activity and then stored in a text file (Microsoft Word; Microsoft, Redmond, CA), and as graphical output that could be exploded to evaluate epochs of ≥ 5 min. An analysis of vector activity for the walk data was also carried out. An additional Excel program (Microsoft) computed and stored data for each day of measurement. Summary data from these files were entered for statistical analysis into Statistical Package for Social Sciences (Version 9; SPSS; Chicago, IL).

For 35 of the 47 subjects, accelerometer measurement was carried out during all 6MDWs 1 week prior to entry into a pulmonary rehabilitation program. In addition, all subjects wore the accelerometer for a 4-day period from Thursday afternoon to Monday afternoon, 1 week prior to entering the program. They were instructed to wear the accelerometer during all waking hours, to carry out their usual activities, and not to remove the device except for bathing and sleep. The subjects recorded wearing duration and comments on wearability and related problems in a daily activity diary that was checked against the accelerometer output when the subjects returned the devices. In order to provide a stable comparison with the time-sensitive activity recall questionnaire, only 3 full days of accelerometer data were used in the analysis (Friday, Saturday, and Sunday).

6MDW: This is a test of functional exercise capacity measured by the distance walked in feet during the longest of three 6-min walks using a standardized format that we have reported previously¹⁵ for instruction, bronchodilator premedication, monitoring, encouragement, dyspnea, oxygenation and pulse monitoring, and supplemental oxygen management and rationale for number of test repetitions. Walking tests have recently gained prominence as a measure of "functional exercise capacity," i.e., the ability to undertake physically taxing activities encountered in everyday life that are not reflected by traditional, maximal exercise testing in those with functional limitation from pulmonary disease. The 6MDW is now widely used in a variety of settings, including pulmonary rehabilitation,¹⁶ determination of eligibility for heart and/or lung transplantation, lung volume reduction surgery,^{17,18} and in predicting mortality in left ventricular dysfunction.¹⁹ Persons for whom supplemental oxygen was prescribed for exertion used oxygen during the walking tests in the same manner and flow rates as prescribed at home. No attempt was made to control nicotine use prior to the test.

Level of Obstructive Pulmonary Disease (FEV₁ Percent Predicted): This is a standardized measure of airflow obstruction, described as the percent of the predicted value of FEV₁.²⁰ The test was carried out prior to the 6-min walk using a spirometer (model 6100; Welch Allyn; Skaneateles Falls, NY) in accordance with American Thoracic Society guidelines,²⁰ and used predicted values developed by Morris et al²¹ that were available in the spirometer software.

Dyspnea Level Today and During the Past 30 Days: These are

Table 1—Sample Characteristics (n = 47)*

Variables	Data	Minimum-Maximum
Age, yr	66.0 (7.7)	48–80
Gender, No.		
Male	44	
Female	3	
Body mass index	29.4 (7.2)	18–50
Pulmonary function		
FEV ₁ , L	1.20 (0.58)	0.43–2.64
FEV ₁ , percent predicted	37 (16)	12–83
Maximal 6-min walk, feet	1,152 (410)	264–2,136
MARQ 3 d, kilocalories	7,906 (2,009)	4,400–12,988
ASEQ	2.45 (2.23)	0–9
Education, yr	12.8 (2.5)	5–17
Employed, No./total subjects	4/47	
Current smokers, No./total subjects	6/47	
Oxygen use, No./total subjects	18/47	

*Data are presented as mean (\pm SD) unless otherwise indicated.

dyspnea scales of the Functional Status and Dyspnea Questionnaire (FSDQ),²² including an estimate of how many times a month that severe to very-severe shortness of breath is experienced, and a 10-point scale of shortness-of-breath severity today.

Activity Self-Efficacy Questionnaire: The Activity Self-Efficacy Questionnaire (ASEQ)²³ is a self-administered assessment of perceived ability to walk distances in a specified period of time, with the individual selecting the longest distance he or she could walk in a given time.

Modified Activity Recall Questionnaire: The Modified Activity Recall Questionnaire (MARQ)^{24,25} is an interviewer-administered questionnaire that assesses energy expenditure in kilocalories from all physical activity undertaken over the 4-day period of accelerometer measurement. Subjects were first asked to identify the nature and duration of all physical activities undertaken over the measurement period. Energy expenditure (kilocalories) was computed for each activity from standardized tables²⁴ in the manner described by Blair et al.²⁵ The kilocalories expended for each activity were summed for each day of measurement to obtain a daily self-report of energy expenditure. Because subjects obtained and returned the accelerometers to research staff and completed the MARQ at slightly different times on measurement days 1 and 5, only a summary of the activity recall from the 3 full days of measurement (Friday, Saturday, and Sunday) was used in the analysis to improve comparability of the activity measures.

Analysis

Descriptive statistics were carried out for all variables. Validity testing and vector analysis used zero-order Pearson correlation coefficients (r). Reliability evaluation was determined with ICCs.²⁶ Data storage, retrieval, and analysis was carried out with the aid of Statistical Package for Social Sciences Version 9 (SPSS) software.

RESULTS

Twelve accelerometers were used, and each subject was assigned the same device for every measurement event. One unit malfunctioned due to failure of one of the three internal accelerometers during a measurement period at home, and the subject was retested with another device.

Descriptive Findings

Forty-seven subjects were studied. The subjects wore the devices a mean of 13.1 h/d (SD, 12.5; range, 1 to 19.5 h/d). Six subjects wore the devices < 10 h: two subjects forgot to put them on on 1 day; the four other subjects stated that they were inactive due to dyspnea and therefore chose not to wear the devices; these data were retained in the analysis. The mean vector magnitude on Friday, Saturday, and Sunday was 46 (SD 25), 42 (SD 25), and 39 (SD 27) VMU/min, respectively (range, 3.5 to 129 VMU/min).

Validity

Content validity, the ability of the accelerometer to represent walking in these relatively incapacitated

subjects, was determined during three sequential 6-min walks. A subgroup of 35 subjects took part in this portion of the study. Two subjects were unable to carry out the third walk due to fatigue. Pearson correlation coefficients between distance walked (in feet) and accelerometer VMU for walks 1, 2, and 3 were 0.84, 0.85, and 0.95, respectively (all $p < 0.001$). Figure 1 is a graphical representation of the highly linear association between VMU and walking distance during three walks.

Figure 2 reflects the accelerometer VMU output (y axes) of three 6-min walks undertaken over a period of 72 min for one subject using a sampling epoch of 1 min/data point. Periods of rest are apparent between each walk. This subject did not stop during the walk tests, and minimal activity after

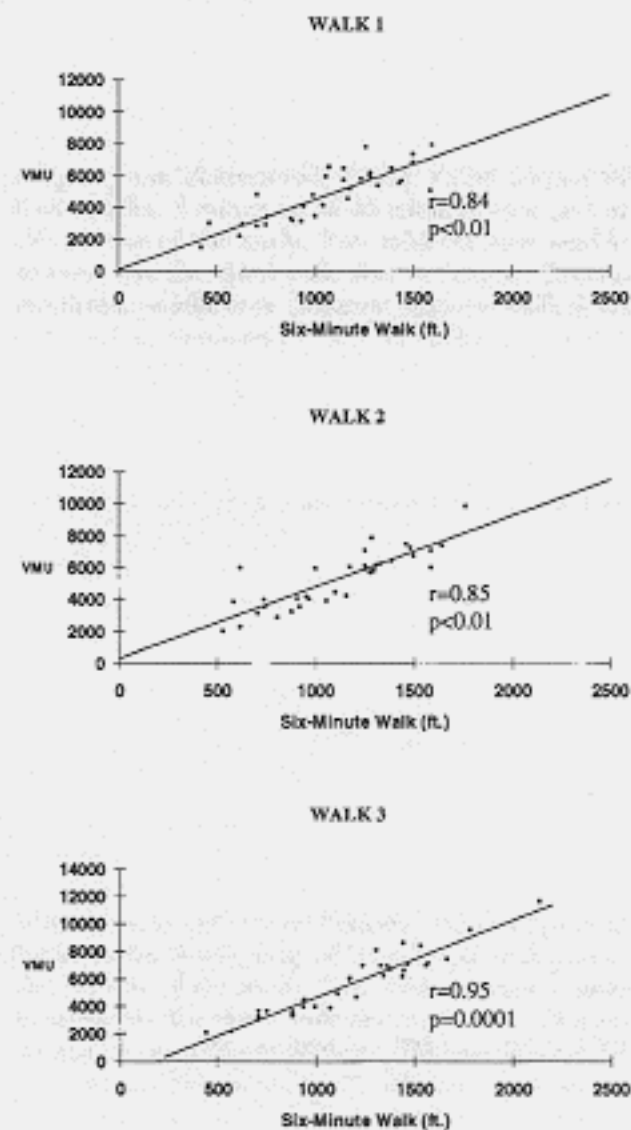


FIGURE 1. Walking activity (VMU) associations with walking distance (in feet) in three consecutive 6-min walks. Pearson correlations and significance levels are indicated for each walk.

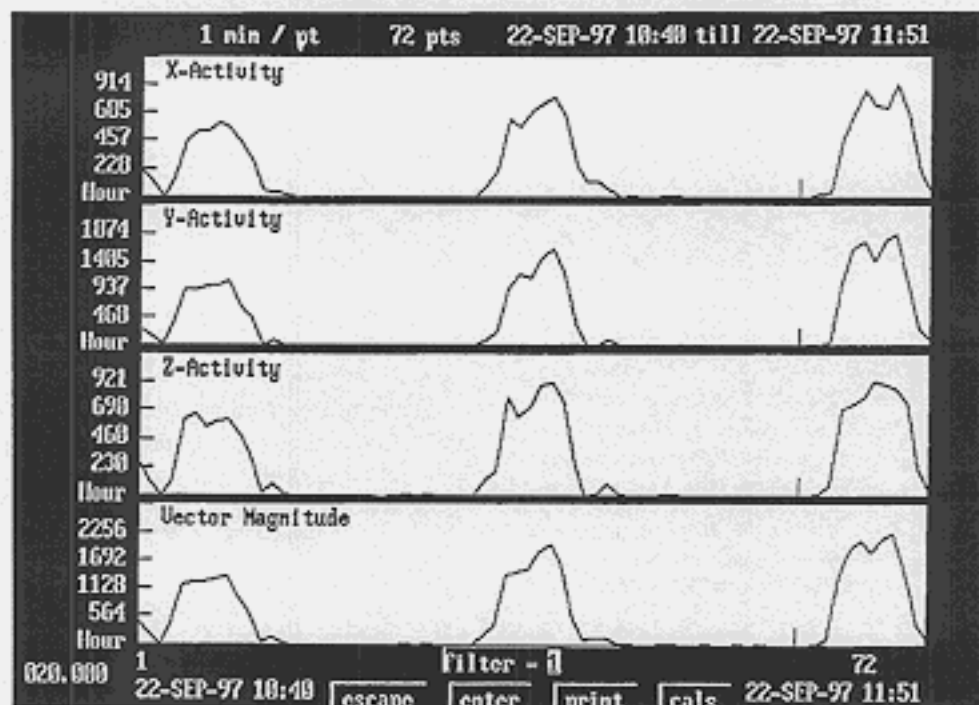


FIGURE 2. Accelerometer output (VMU) for three successive 6-min walks (y axis) conducted over a period of 70 min (x axis), with rest periods between each walk. X-activity, Y-activity, and Z-activity represent movement in anterior-posterior, vertical, and lateral planes, respectively. Vector magnitude depicts the integration of all planes.

walks 1 and 2 represents a brief walk to a place where subjects were allowed to rest at the conclusion of the walk. This Figure reflects the potential utility of the device to document qualitative properties of walking, including pacing effects such as speed, reflected by changes in the y axis (VMU), as well as the placement and the duration of rest periods.

Concurrent validity was tested in all 47 subjects by determining the association between accelerometer total activity (VMU) over 5 days of free living at home with maximal 6MDW, level of obstructive pulmonary disease (FEV_1 percent predicted), dyspnea (FSDQ, dyspnea today and during the past 30 days), activity self-efficacy (ASEQ), and activity recall (MARQ). The data indicated good compliance with wearing the device during waking hours, with the exception of two subjects who wore their devices < 10 h because they forgot to put them on. Significant correlations were evident between accelerometer activity at home, level of obstructive pulmonary disease ($r = 0.62$; $p < 0.001$), exercise capacity ($r = 0.74$; $p < 0.001$), dyspnea over the past 30 days ($r = -0.29$; $p < 0.05$), and self-efficacy for activity ($r = 0.43$; $p < 0.01$). Dyspnea today ($r = -0.27$; $p =$ not significant [NS]) and activity recall ($r = 0.14$; NS) were not correlated with accelerometer measurement of activity. Figure 3 represents the association between accelerometer

activity at home and exercise capacity measured by maximal 6-min walk.

Table 2 includes a summary of the correlations between accelerometer activity and other indicators of functional status.

Reliability and Stability

Test-retest reliability of the accelerometer using rICC was evaluated in 35 patients during three sequential 6MDWs. The rICC for VMU during walking tests was 0.84, and reflected the expected improvement with each successive walk due to learn-

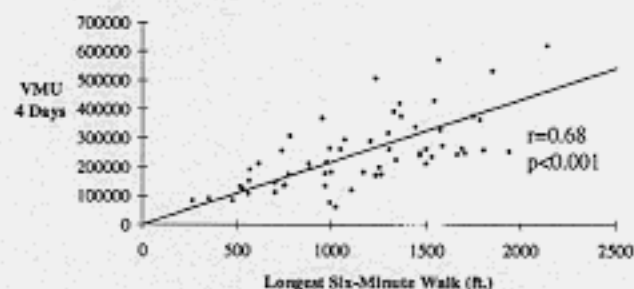


FIGURE 3. Linear association between accelerometer activity at home (VMU) for 4 full days at home, and exercise capacity represented by the longest 6-min walk (in feet). The Pearson correlation was $r = 0.74$; $p < 0.001$.

Table 2—Pearson Correlations (*r*) Between Accelerometer Activity Over 3 Full Days, and Other Measures of Functional Status

Variables	Accelerometer Activity (VMU) Pearson Correlations (<i>r</i>)
Exercise capacity (longest 6MDW in feet)	0.74†
Level of obstructive disease (FEV ₁ percent predicted)	0.62†
Dyspnea (FSDQ)	
Today	-0.27
Over past 30 d	-0.29*
MARQ 3 full d (kilocalories)	0.14
ASEQ	0.43†

**p* < 0.05.

†*p* < 0.01.

‡*p* < 0.001.

ing. Distance walked for the three walks was also strongly correlated (*r*ICC = 0.93), and demonstrated longer walking distances with each successive walk consistent with the learning effect inherent to this test (Table 3).

Stability of accelerometer measurement of free-living physical activity was also evaluated over 3 full days at home (*r*ICC = 0.69). Days 2, 3, and 4 of at-home measurement (Friday, Saturday, and Sunday) were used because on the first and fifth days, the subjects wore the accelerometers for different periods of time.

Vector Analyses

Pearson correlations between VMU and movement activity (in feet) generated during the third 6MDW (*n* = 33) by each of the three vectors are shown in Table 4. All the vectors were significantly intercorrelated, and correlations with the integrated measure (VMU) ranged from *r* = 0.91 (Z vector) to *r* = 0.99 (Y vector).

DISCUSSION

This study evaluated reliability, validity, and stability of a triaxial accelerometer for measuring human movement in very sedentary COPD outpatients under two measurement conditions: the 6-min walk and during daily activity at home. The participants, most of whom had severe to very-severe obstructive disease,²⁷ were similar to others studied at entry to pulmonary rehabilitation in terms of age, level of obstructive disease, symptom experience, and exercise capacity.^{13,16} We determined that the accelerometer effectively measured bodily movement during a standardized walk test in this sedentary population and

quantitated daily activity at home precisely. Subjects reported that the devices were not uncomfortable to wear and were not unduly intrusive.

Vector magnitude, a "raw" index of physical movement, was chosen *a priori* as the accelerometer output measure of choice instead of energy expenditure indexes of total or activity calories. The reason for this choice was the probability that an energy expenditure prediction formula would underestimate energy consumption in persons with COPD who have higher oxygen utilization due to ventilatory dysfunction. More recently, Fehling and associates²⁸ found that the proprietary Tritrac formula underestimated energy expenditure compared to indirect calorimetry during treadmill walking and stepping exercise in older adults, and cautioned against using the device to measure energy expenditure in this group. The use of vector magnitude as the measure of activity instead of activity calories and total calories has also been recommended for neurologically and other physically impaired persons who have inefficient energy utilization during walking and routine daily activities.¹⁰ Oxygen "inefficiency" in COPD is also consistent with the lack of a significant association between accelerometer-measured physical activity in vector magnitude and the MARQ, which is based on energy consumption in metabolic equivalents over 3 days of measurement.

The highly linear association between accelerometer activity (VMU) and distance walked during three walk tests suggests that the accelerometer is a valid measure of physical movement during walking in this functionally-limited group. This finding is fundamental to confirming its relevance as a measure of human movement, because walking is a ubiquitous activity and is an important process and outcome measure for pulmonary rehabilitation and a variety of other interventions. The reliability of the measure during the three walking tests was also high (*r*ICC = 0.84), with some variability in the measure probably due to the systematic improvement in walking distance with successive walks due to learning. In Figure 1, scatter around the regression lines is clearly minimal and not related to maximal distance walked. This finding was most notable in the third walk, which is usually the longest walk achieved when using a 3-walk protocol.¹⁵ Data analysis of vector magnitude during the 6-min walks revealed previously unanticipated qualitative dimensions of this measure. Accelerometer output during a typical 6-min walk (Fig 2) provides a graphic portrayal of strategies used to "cover more ground," including increasing walking speed, taking no rests, and interval pacing, which has the potential for use as an adjunct to counseling patients in adopting more efficient, energy-conserving walking techniques.

Table 3—Reliability of Accelerometer Measurement During Three 6-min Walks (n = 35)*

Variables	Walk 1	Walk 2	Walk 3	rICC
Distance walked, feet	1,017 (383)	1,074 (376)	1,155 (400)	0.93
VMU	5,177 (2,317)	5,660 (2,579)	6,016 (2,833)	0.84

*Data are presented as mean (SD).

Concurrent validity of the accelerometer for measuring daily activity during free living at home was also suggested by the good correlations of vector magnitude with selected measures of functional status. Perhaps most notable in these findings are the fairly robust correlations between accelerometer activity and exercise capacity (6MDW) ($r = 0.74$; $p < 0.001$) and FEV₁ percent predicted ($r = 0.62$; $p < 0.001$). The close association between accelerometer activity at home and 6-min walk supports the observation that the 6-min walk closely parallels the level of activity that patients are most likely to perform regularly in their daily lives, and may be superior to conventional maximal exercise testing in this regard.¹⁵ In COPD, this measure may also be more reflective of their level of obstructive disease than maximum exercise capacity measured on the same day; this observation is supported here by a lower correlation between FEV₁ and 6-min walk than FEV₁ and accelerometer activity at home ($r = 0.41$; $p < 0.01$ compared to $r = 0.62$). Preusser and Winningham⁵ used a Caltrac accelerometer to measure 4 days of activity at home in a group of 17 COPD patients and found significant correlations with inspiratory muscle strength ($r = 0.66$; $p = 0.004$) and inspiratory muscle endurance ($r = 0.71$; $p = 0.001$); like the present study with its high correlations between FEV₁ and daily activity ($r = 0.62$; $p < 0.001$), both measures of movement appeared to be strongly associated with pulmonary function. Unlike the present study, Preusser and Winningham⁵ found only modest correlations between daily activity and exercise capacity using a 12-min walk ($r = 0.50$; $p = 0.04$). These findings might be explained by the relatively small number of subjects in their study ($n = 15$), and also because the Caltrac accelerometer may have been less sensitive to movement in this sedentary group.

The report of dyspnea, both today and over the past 30 days, was only modestly correlated with daily activity and was negatively associated with activity levels, with lower levels of activity associated with higher levels of perceived dyspnea. Dyspnea is known to be highly variable in this population, and the time frame for dyspnea measurement differed from the 4 days of accelerometer activity, possibly accounting for these weak associations. Nonetheless, these findings relative to accelerometer activity tend to support the contribution of dyspnea to physical incapacity in this group of stable COPD patients.

The moderate correlation between accelerometer measurement of activity and walking self-efficacy ($r = 0.43$; $p < 0.01$) supports the assertions of Bandura,²⁹ that the actual performance of a skill (walking, being physically active) is partially dependent on the perceived ability of the individual to undertake and persist in the achievement of that skill. This finding supports the use of self-efficacy modeling in interventions to promote walking and related tasks. Vector magnitude, the formula-free index of movement independent of energy expenditure, was not correlated with activity recall (MARQ), which measured activity undertaken over the same 3-day period as accelerometer activity measurement ($r = 0.14$; $p = \text{NS}$). One possible reason for this lack of association between the self-report and direct measurement of activity is that the accelerometer more precisely quantitates the many small, unnoticed, and undocumented movements such as short walks and the like, undertaken and unnoticed in the course of the day. Failure to faithfully represent these numerous periods of low-level activity probably contributes to the weaker association between activity self-report and accelerometer activity measurement. The MARQ was very difficult for this group to complete because of the memory-dependent nature of the task of recalling

Table 4—Accelerometer Vector Analyses: Correlations During Third 6-min Walk (n = 33)

Variables	VMU	Anteroposterior (X)	Vertical (Y)	Mediolateral (Z)
Anteroposterior (X)	0.93*	—		
Vertical (Y)	0.99*	0.90*	—	
Mediolateral (Z)	0.91*	0.76*	0.87*	—
Walk distance (feet)	0.95*	0.79*	0.95*	0.96*

* $p < 0.001$.

specific low-level activities and their duration, which may also contribute to error variance in the instrument. Modest correlations between accelerometer activity and memory-dependent questionnaires have been observed by other investigators, in even younger subjects.⁴ It has been suggested that the failure of these methods to correlate well should be attributed to the inherent difficulties with the recall questionnaires themselves, rather than measurement flaws in the accelerometer.¹¹

Although it was expected that this sedentary group would manifest a low level of daily activity, it was surprising that the measure of movement in VMU was even lower than that of moderately-active nursing home residents studied by Kochersberger et al,⁹ who had a mean of 46.6 VMU/min (SD ± 15), compared to our study group, who had a mean of 42 VMU/min (SD ± 26). Compared to functionally incapacitated MS outpatients studied by Ng and Kent-Braun,¹⁰ the COPD group were only about half as physically active (60×10^3 VMU/d [SD, 37×10^3]), compared to the MS group (approximately 110×10^3 VMU/d [SD, 50×10^3]). Our findings support the observations of these investigators, that the accelerometer studied here is sensitive to low levels of physical activity and therefore appropriate for use with sedentary populations.

General limitations of this study include the use of a study group composed primarily of men, although gender has not been identified as a factor contributing to accelerometer measurement variability in other accelerometer research. With respect to accelerometers, a number of limitations should be considered with respect to the measurement of free-living activity. First, these devices are likely to poorly represent energy expenditure from moving up inclines (such as walking hills or stairs) and exercise (such as weight-lifting or stationary cycling) that does not involve total body movement. The present study suggests, however, that walking, the most prevalent exercise suggested by health-care providers and undertaken by clinical groups is represented well. Lack of compliance with wearing accelerometers has been identified as a limitation in other work using this technology.⁹ In the present study, care was taken to compare subjects' self-report of awakening and retiring for sleep with the accelerometer data; with few exceptions, accelerometer data coincided closely. Nonetheless, two subjects forgot to wear their accelerometer, and others who were ill and inactive on one or more days of the study wore their accelerometers < 10 h. Another limitation regarding accelerometer methodology is the potential error contribution of vibration and movement from riding in cars and other vehicles. Bouten et al,⁸ who compared daily physical activity measured by a similar triaxial

accelerometer (Tracmor; sampling range, 0.3 to 20 Hz) to doubly labeled water methodology, found that vibrations introduced from riding in vehicles (buses, motorbikes, etc.) produced high values for movement that were not seen during voluntary human movement. To compensate, they excluded data over a certain maximum to correct for these findings. The Tracmor device, with its wider sampling range (0.3 to 20 Hz) may be more sensitive to higher-frequency vibrations, compared to the Tritrac R3D, which measures across a more limited frequency range (0.1 to 16 Hz). Nonetheless, in the present study, there was still a significant correlation between the vector magnitude over 4 days and the total driving time spent in an automobile ($r = 0.66$; $p < 0.001$). This finding may be attributable to the probability that physically active people are more likely to drive vehicles and use motorized transportation in general. This issue deserves further study. In addition, signal error may result from bumping or dropping the instrument. Subjects in the present study were instructed not to unnecessarily handle the devices while wearing them, or to take them from the protective pouch. Bumping or dropping the devices would probably occur randomly in all subjects and therefore not be a source of systematic error. Another major disadvantage of the Tritrac accelerometer is that it is about five times as expensive as the Caltrac and other unidirectional accelerometers. One might ask what measurement advantage a triaxial accelerometer provides compared to a unidirectional accelerometer? In the present study, it was apparent that the y vector, which is oriented to measure vertical movement, was virtually identical to the integrated measure, vector magnitude (VMU) with correlations with distance walked during the final 6-min walk ($r = 0.99$; $p < 0.001$). A study of accelerometer activity in obese children by Coleman and colleagues,¹² using an earlier version of the Tritrac accelerometer, found that the anteroposterior vector was highly correlated with vector magnitude ($r = 0.98$; $p < 0.001$) and accounted for the same amount of variance (34% and 36%, respectively) in unadjusted heart rates. These findings probably reflect major differences in activity patterning between these two diverse groups, and suggest that in the COPD group, a single, vertical accelerometer might be just as useful as the Tritrac accelerometer for walking activity. This question deserves further study.

This preliminary study suggests that the triaxial accelerometer is a valid measure of the fundamental human activity of walking and, similar to the 6-min walk, provides a previously unappreciated view of everyday functional performance. It also suggests that the device has good concurrent

validity, based on its fairly robust associations with exercise capacity and level of obstructive pulmonary disease and its moderate associations with walking self-efficacy and dyspnea, and is far superior to currently used self-report methods relying on memory. This methodology is potentially useful in risk modification, by identifying individuals and groups whose sedentary lifestyles pose a risk to their health, and as an outcome measure in intervention trials to improve mobility and function in persons with cardiopulmonary illness, neuromuscular impairments, and the frail elderly. It represents a novel strategy to measure an important dimension of functional status and quality of life not previously well-quantified.

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